Review of the Technical Issues Associated with the Construction of a Solar Neutrino TPC

G. Bonvicini[a], D. Naples[b], V. Paolone[b]

[a] *Wayne State University, Detroit MI 48201*
[b] *Univ. of Pittsburgh, Pittsburgh PA 15260*

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Abstract

In this note the issues surrounding the realization of a solar neutrino TPC are reviewed. The technical challenges can be summarized as building a very large TPC within the low background constraints of solar neutrino experimentation.

1 A comparative review of a solar neutrino TPC.

A TPC is radically different from all other solar neutrino experiments in that it measures the direction of the target particle (the electron). It also has a much finer granularity than other detectors, easily distinguishing between electron and non-electron events, and events of multiplicity one and events of multiplicity two or higher.

Directionality provides much of the physics reach (by measuring the neutrino energy and average flavor). From a feasibility point of view, however, we are particularly interested in the effect that directionality has on background suppression. First, directionality allows a direct reduction of backgrounds by a factor of four to ten. Only events pointing in a cone directly opposite the solar angle are considered, with a $\cos\theta_{\odot}$ cut ranging from 0.5 to 0.8. Second, directionality allows us to measure, up to statistical fluctuations, all the backgrounds that affect the experiment. By "all the backgrounds" we mean both internal (^{14}C, ^{85}Kr, Rn) and external backgrounds (^{238}U, ^{232}Th, ^{40}K, and cosmogenic activity in the surrounding materials). Finally, since the target is mostly helium (we consider only He/CH_4 mixtures, with helium at least 90% of the mixture) internal cosmogenic activity is virtually absent. This fact, plus the unique direct measurement of backgrounds translates into very modest depth requirements.

While low background experimentation applies stringent constraints to the design of this detector, there are several aspects in which this TPC is remarkably simple to build and operate, and these include most of the major problems normally encountered by large TPC. The advantages are:

1. The TPC is located underground, inside a completely enclosed Faraday cage. We can reasonably assume that the noise seen by the TPC will be generated only by its internal components. A complete list includes amplifier noise, and capacitive noise from wires or strips plus cables. Both can be reliably predicted at or below a few thousands electrons for an integration time of order 250 nsec.

2. There are no constraints from other surrounding detectors. The HV can be brought in with a very large cable (perhaps one foot in diameter), and the HV degrader can be embedded in the 1-1.5 meter thick plastic shielding, providing excellent electrostatic stability in the drift HV system.

3. The expected low rates ($\sim$ 0.1Hz) virtually eliminate charge build-up problems. One can design a detector plane where the wires are not directly facing other electrodes, as described below, providing excellent electrostatic stability in the detector plane.

4. The expected low rates virtually eliminate any chance of detector ageing, allowing the option ot use materials such as uncoated steel wires or polyethylene, which would age a chamber rapidly in an accelerator environment.

5. A precision calibration is provided automatically by cosmic rays and other background events, while calibration complexity is reduced by the lack of a significant magnetic field.

The TPC has one drawback; it is not self-shielded. The region immediately surrounding the active volume contains significant amounts of materials which are not as pure as the material in the fiducial volume (the TPC cage, wires, strips, and the HV grid at least). This translates into substantial limitations on which materials can be used in the surroundings. We will discuss the backgrounds, materials, and their purities in Section 3.

While no TPCs of this scope have even been built, invaluable information about the MUNU experiment was provided by C. Broggini[1]. This is the largest underground pressure TPC built so far (about $2m^3$), it collected data on low-energy $\bar{\nu} - e$ scattering, and shared many of the problems we will face in the near future. We refer to their experience throughout the paper.

2 The TPC as a Detector.

A sketch of the gross features of the proposed TPC is shown on Figure 1. It consists of a cylinder twenty meters long and between 14 and 20 meters in diameter (depending on the final choice of detector parameters). It will contain between 7 and 10 Tons of gas, and will be separated from the rock by 2.5 to 3.5 meters of water equivalent of high purity shielding (in the figure, about 1.5 meters are provided by the steel tank, and about 1.0 meters by high purity plastics/water). The mid plane is occupied by a high purity metal grid, at a voltage of -100 to -200 kV. HV elements are recessed in the shielding. The TPC cylinder itself is enclosed in an external pressure vessel. There is a slight overpressure inside the TPC, compared to the rest of the pressure vessel. Teflon gaskets are used to seal the juncture of the barrel and endcap.

The overall TPC design philosophy is one of a device that is as stripped down as possible, minimizing the number of electronic channels and materials coming into contact with the gas. The end caps are the detector planes and contain a single set of wires and a single set of strips, to be discussed in more detail later. The wires reconstruct the (x, z) profile of a track, and the strips the (y, z) profile of a track, where z is the drift direction. The direction and energy of a track is reconstructed by combining both track views. Assuming a pitch of 2 millimeters for wires and strips, the TPC needs between 28000 and 40000 electronic FADC channels.

The gas mixture consists of boil-off helium in bulk, with a small admixture of natural gas from a deep well boiled off at 112K (in practice, pure methane). Boil-off at low temperatures eliminates all metals and many radioactive or electronegative gases, from water vapor to radon.

Total gas volume and density determine the total number of target electrons for solar neutrinos. These are determined by the gross detector parameters; total drift length, wire/strip length, and gas pressure. The total drift length is limited by diffusion considerations on the drifting electrons. We have chosen a maximum drift length of ten meters which corresponds to a maximum drift time of 8.3 msec at 100 kV (measured drift velocity 1.2m/msec). The total diffusion over ten meters drift for an operating pressure of 10 atm is 4.3 mm and changes only by a few percent at higher fields. The gas pressure is limited by a requirement on minimum track length to achieve our desired angular resolution, and the wire length is limited by the RC constant being of order of the FADC

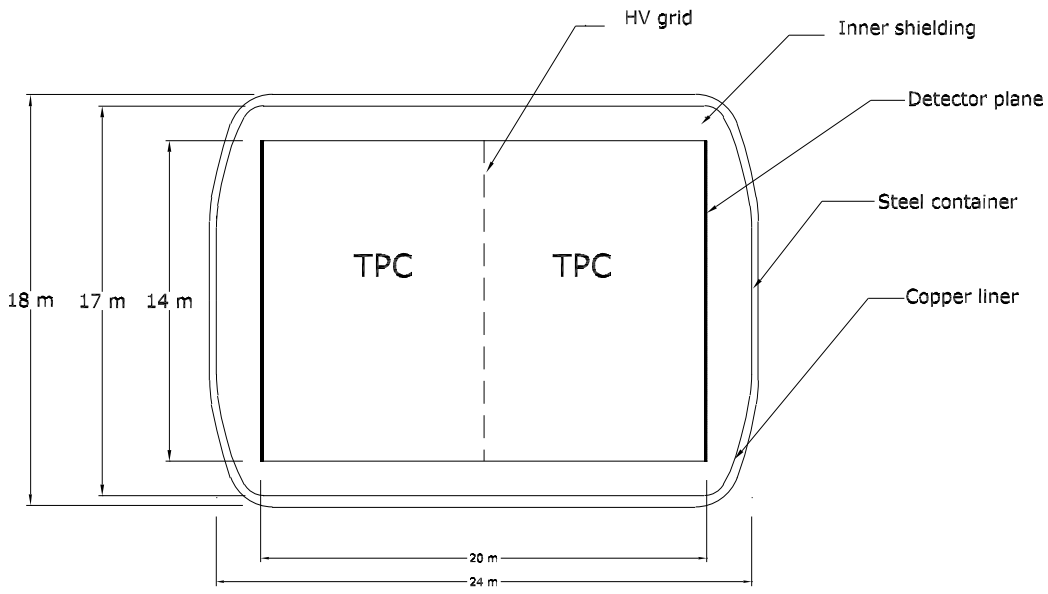

Figure 1: Sketch of TPC cage and surroundings.

timing bucket (200-300 nanoseconds). The strip length is not significantly limited at this point in time.

We will discuss the design of a TPC with 20m length, 14m diameter, 2mm wire and strip segmentation, and 10 atm of He(97%), CH4(3%) in this document. We also assume for presentation purposes that the TPC is located at a depth of 2500 mwe.

2.1 Detector Plane and Grid

Except for the central grid, which defines the HV midplane and will be made of the cleanest metal wire available (probably OFHC wire), the detector planes contain all the metal parts in the immediate vicinity of the TPC.

The detector plane is shown schematically in Figure 2. In its minimal configuration it consists of one plane of 20μm wires, and one plane of strips, separated by about 0.6 millimeters, 0.1 millimeters of which is in the form of a plastic foil insulating the two planes. The wires are held at a voltage of approximately 2-2.5 kV, and the strips are held at a negative voltage of about 1 kV with respect to the wires, which forbids the presence of field lines breaking the wire plane. There is a simple grid at 5 mm distance, separating the drift and gain region.

With the parameters discussed above, we expect a gain of 5×10^4 to 10^5, with a pulse time constant of 200-300 nsec for the wires[2]. By comparing to the expected electronic noise numbers, we expect close to 100% efficiency for the wires, while the coupling and efficiency for the strips is 60% and 80%[2]. The RC of the strips is much smaller than that of the wires and depends on the thickness of the strip.

The wires can be made of any of the following three materials: steel, Cu/Be alloy, or uncoated tungsten. The latter is the material of choice for MUNU, and proved to be a radiopure material by MUNU standards. The other two are choices based on the known high purity of steel and copper. All three types of wires are readily available commercially and need to be tested for radiopurity at a suitable facility. The strips are made of high purity OFHC.

There is a premium in being able to assemble and disassemble the detector plane and grid quickly: a quick assembly reduces initial contamination of surface by radioactive dust or radon daughters, and a quick disassembly allows to fix contamination problems by dust or radon, or to change the active elements if they are found to be unsuitable. Therefore a TPC were all parts are snap-on is considered.

The MUNU experience proves that the grid needs to be removable quickly. In one large radon contamination episode (which was later tracked to the Oxysorb cartridge in use then), radon daughters, having been ionized in the nuclear decay, drifted as ions to the grid where they accumulated, probably by bonding chemically to the metal (polonium has the same valence as oxygen). A circular curtain rail scheme, with a pulling cord and one-plug connection to the HV, should suffice.

The wires need to be strung without use of epoxy or solder. At this time a strategy is considered, where they are cut to measure and welded by electron gun to a small pin of the same material at each end. The pin locks in an appropriate notch at the end plane rim. In the case of tungsten

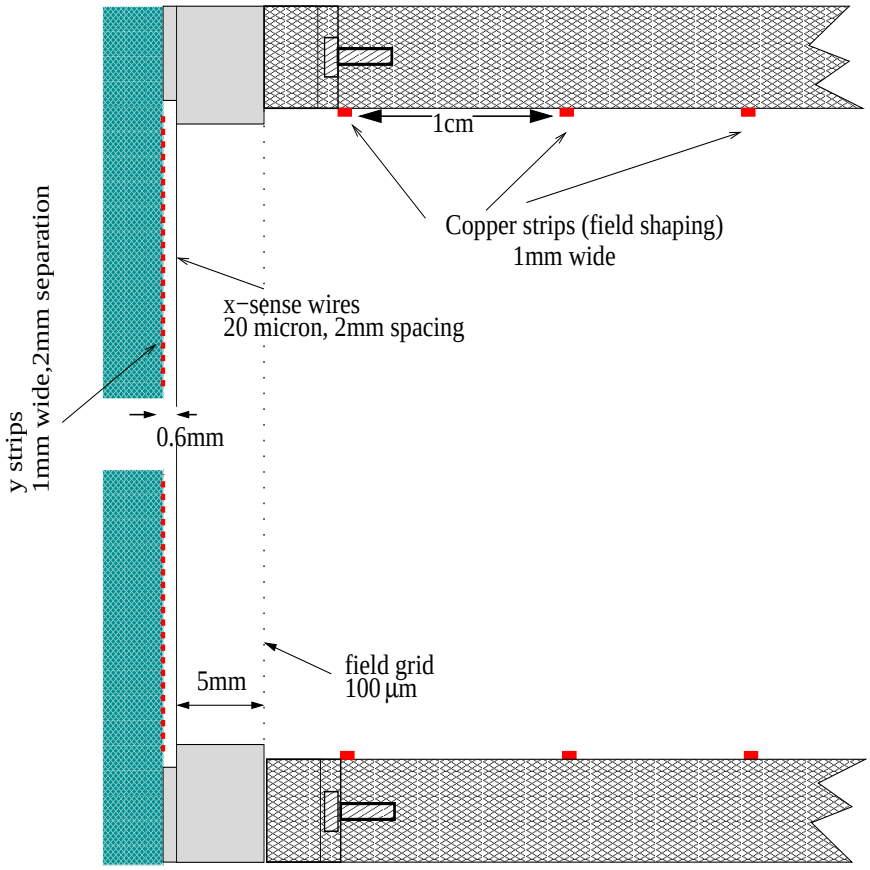

Figure 2: Sketch of detector elements in TPC end cap planes.

htb

Table 1: Boiling points of gases of interest for the TPC.

Gas	Boiling Point (K)
Methane	111
Radon	211
Krypton	116
water	373
oxygen	87
CF_4	145

wires, the standard tension of 62 grams is equivalent to a 1% elastic elongation. Therefore a 14 meters wire needs to be made 14 cm shorter if it is to be strung at that tension, and that is what we intend to do. In fact, we consider a tension of 40g, to diminish the failure rate, with the wires strung horizontally and supported by 1 millimeter thick comb every 67 cm.

The combs, hung vertically, serve two purposes: they hold the wires, and they pin down the plastic sheet that separates electrostatically the wires and strips. This sheet can be made of polyethylene, nylon, or kapton. In the case of kapton, there exists the possibility of simply electrodepositing the very long copper strips on one side, if radiopurity can be maintained through the deposition process. The strips RC constant can be controlled by depositing a thicker layer of copper. Another possibility is to have a clean plastic sheet, and a grooved wall behind the sheet. The strips will then fit into the grooves, pinned at the top and hanging vertically. The final design choice will depend on achievable radiopurity and ease of assembly.

2.2 Gas System

The special nature of this TPC places a particular importance on this part of the apparatus. A gas system should basically consist of:

1. $0.05\mu m$ dust filter
2. Oxysorb cartridge
3. Cold trap with charcoal filter operated just above the boiling point of methane, or 112K.

The interaction between these parts of the gas system and further issues of how they should be implemented are discussed more below. For reference, the boiling point of methane is compared in Table 1 with the boiling point of other relevant compounds.

The main requirement on the gas mixture is radiopurity. The gas mixture can be obtained by mixing boil-off helium with deep well natural gas boiled off at 112K, and by storing the mixture in a low-radon vessel and possibly underground. The mixture is non-toxic, non-explosive, and non-flammable, minimizing hazards in case of a leak. He/CH_4 has sufficient gain[2], with wire HV at around 2.2 kV[2] and low diffusion[3, 4].

Electron lifetime for a drift of ten meters distance has not been measured directly, however, there is substantial evidence that it can be achieved. Icarus Collaboration has reported results for 1.4 m drift in liquid Argon, a far more demanding medium for electron drift with significant solubility for major electronegative compounds (such as oxygen). [5]. Also, 2.0 to 2.5 meters drifts have been obtained by major TPCs such as ALEPH and STAR, with electron attenuation lengths exceeding 10 meters[6, 7].

Considerable attention needs to be devoted to the gas impurities which can degrade collection efficiency. In this subsection we discuss those electronegative impurities (like water or oxygen) that can absorb drifting electrons. The main detector component that can introduce these impurities could be acrylic, which was found to be radiopure by the SNO collaboration (who used it for their heavy water vessel) and then was chosen by MUNU[1] as the TPC cage material. In the mixing process used in producing acrylic, micro-bubbles of unmixed resin persist and become permanent production centers of both water and oxygen.

To keep oxygen at workable levels, in MUNU, the gas was continuously recirculating through an Oxysorb, [1] with a recirculation time of 6 hours[1]. In our case, recirculation time would be on the order of 90 to 120 hours, if we assume the same typical contamination and scale for the surface/volume ratio. There are advantages in obtaining a much longer circulation time, as discussed in the background section below. Ideally, we would like to clean the gas from dust ONCE, clean the gas from oxygen as close as possible to ONCE, and have the cold trap on ALWAYS.

The gas system is also slightly complicated by having two circulation systems, a helium-methane inside the balloon and another mixture (helium with perhaps nitrogen, same proportions) outside the balloon and at a slightly lower pressure. Helium moves freely across the balloon but the other gases do not, and as a result helium is constantly leaking out of the TPC.

We are also considering polyethylene as an alternative to acrylic for TPC balloon material. Polyethylene has the advantage that it does not contain oxygen in the bulk material, and does not produce oxygen containing compounds long term (once gases embedded in the bulk material have diffused out).

We expect to have substantially less electronegative compounds in the gas than in previous TPCs, for the following reasons in order of increasing importance:

1. Our TPC will not contain any epoxies. These contribute as additional source of both water and oxygen.

[1] However, it is a possible risk that this could introduce radioactive impurities [1].

2. Our gas will be continuously recirculated through a cold trap, at a temperature sufficient to remove both impurities as well as some radioactive gas contaminants.

3. Alternative balloon material, polyethylene, discussed above.

4. Slight Helium overpressure will further inhibit the entry of gases from the balloon from entering the active volume.

2.3 Achievable TPC performance.

100 keV tracks are considered the TPC ultimate benchmark. Such a track at 10 Atm has a total length of 9 centimeters and generates 2500 electrons that will drift to the anode while diffusing. Resolution effects are dominated by angular resolution. The angular resolution, in turn, depends significantly on multiple scattering, and the aspect ratio of the track (how long it is, compared to how wide it is - basically, the ratio of track length versus diffusion).

The average diffusion is equal to 2/3 of the maximum diffusion, or 2.8 millimeters. 95% of the electrons will be included within two standard deviations in each direction. Therefore the typical 100 keV track will occupy a volume of $1.1\times1.1\times9$ cm^3 (the third component is along the track direction). The TPC samples small unit volumes where two dimensions are given by the wire and strip pitch, and the third is equal to the drift velocity times either the RC constant or FADC bucket (they are about the same number).

Thus, the sampled volume is approximately $0.2\times0.2\times0.03$ cm^3 (the third component is along the drift direction). There is an estimated total of 9000 samples in a 100 keV track, to be compared with the existing 2500 electrons or 0.28 electrons per unit volume. In fact, the head of a track has a ionization density substantially lower than the tail, bringing the ratio down to close to 0.1 electrons per unit volume.

The estimate above shows that even a wire TPC recovers, for the most part, single electron information[4] for tracks that have diffused considerably. Tracks with less diffusion do not have single electron determination, except in the tails of the diffusion distribution, but are also narrower and ultimately better determined. We expect a somewhat slowly varying resolution across the TPC, where the dilution due to diffusion is partially compensated by the turn-on of single electron resolution. Note that measuring the two ((x,z) and (y,z)) track profiles is a factor $\sqrt{2}$ worse than determining each single electron in (x,y,z) - however such a loss is substantially smaller than the gain of working at lower pressure compared to the original design.

It is unclear, at this time, what is ultimately the average angular resolution, what is the distribution of angular resolutions for a large number of tracks, and how the resolution is related to χ^2-like quantities that can be extracted from the data themselves. The multiple-scattered track is in fact a fractal of dimension two, and there is no book on how to fit (let alone extract maximal information from) such a thing. It will take substantial software development to arrive at a final answer.

We wish to point out at this time that, if extra resolution is needed to effectively cover the physics, we can always build a lower pressure, larger TPC. We estimate conservatively a P^{-2} dependence of the resolution on pressure. From our simulations we estimate a resolution of 15 degrees at 100 keV and 10 Atm, and decreasing like $T^{-0.6}$, T being the electron kinetic energy.

2.4 TPC Calibration.

We have touched on calibration issues in the Physics Reach Paper[9] (attached). Clearly identified background events provide gold plated calibration events. Assuming a depth at which the cosmic rate through the chamber is 0.1Hz, and where the bulk purity of the materials surrounding the TPC is 10^{-12}g/g of ^{238}U, yearly rates of interesting events are as follows:

1. 3×10^6 cosmic rays providing wire and strip gain calibration.
2. 7×10^5 cosmic rays crossing the grid or one of the planes providing diffusion and drift velocity calibration.
3. 3×10^5 cosmic rays crossing both the grid or one of the planes, providing drift and diffusion calibration over the whole drift.
4. 3×10^5 delta rays with $T > 100$ keV, where angle and kinetic energy are kinematically related.
5. 1×10^4 double Compton scattering, where events of multiplicity two are observed and are correlated in angle. Several kinematic relations can be used to constrain the angular resolution and energy resolution at the 1% level.

We expect no significant error due to incomplete knowledge of the TPC performance.

2.5 Pressure Vessel & Engineering

The pressure vessel consists of a copper or steel liner which is airtight and pushes against the steel tank. The copper liner would be assembled in situ out of large copper sheets which are welded together. Defects would be seen by using Thermal Wave Imaging (TWI), a technique that can easily find 10 microns hairline cracks or less in the field.

A first test of copper welded plates against TWI was performed at WSU and was completely successful - areas where the welding was incomplete were clearly seen, while areas with good welding tested positive. We have a CD with six TWI movies that will be made available on the web within the next month. Currently, steel sheets and OFHC sheets are being tested at WSU to decide which liner is best suited to the pressure vessel.

Once the pressure liner is completed, it becomes a high class clean room while the detector is built from the inside out. Because the steel tank is by far the strongest part of the device, there

might be a need to have large rods, made of the same material as the liner, mechanically connected to the tank, welded to the liner, and available to support parts inside of the liner.

In principle, the plastic shielding of Figure 1 is assembled via roman arch assembly and any extra support, if needed, is provided by the rods. The TPC cage is supported by the plastic shielding. The total pressure due to the strung wires is a modest 280 kg per side, whereas the total weight of the plastic shield is 1400 Tons.

3 Backgrounds.

The signal sample is defined as contained events of multiplicity one. In addition these events must have clearly elongated tracks, and a dE/dx profile compatible with the electron hypothesis. These simple requirements eliminate the backgrounds due to α's, neutrons, cosmic rays, and β radiation entering through the TPC barrel.

The two classes of events that remain as background are single Compton electrons, regardless of the γ source, and β-decay within the active volume. Some sources, that do not produce backgrounds per se but could generate unacceptable noise levels, are also discussed in the following sections.

γ rays are produced predominantly in the radioactive decay of ^{238}U, ^{232}Th, and ^{40}K, with roughly 2, 2 and 1 gamma's of suitable energy produced in each completed chain respectively. The ^{238}U γ spectrum is shown in Fig. 3 of Ref.[8].

^{238}U and ^{232}Th also produce a small amount of fission neutrons, which do not produce a background directly but are not attenuated much by high Z materials and generate penetrating γ of several MeV on being captured. The effective rate of neutrons does depend on the exact composition of the producing material, however, it is typically down by a factor of 1000 compared to the γ rate.

In the accompanying paper[9], based on the analysis by R. Kessler[8], it was found that a total background rate of about 150 events per day above 100 keV and before directional cuts generate a small background subtraction error over one year (and negligible over the lifetime of the experiment). To achieve this rate we must maintain a limit of $\sim 0.5\mu$grams of ^{238}U equivalent, uniformly distributed on the inside wall of the TPC cage, plus a maximum ^{14}C to ^{12}C ratio of 10^{-19} in the TPC gas.

^{14}C, however, is a β emitter and in general can only generate a background if it forms part of the TPC gas mixture or the electron produced enters the active TPC region through the detector endcaps.

In this Section, we work our way to Table 2, that characterizes the background levels that need to be obtained for this TPC to produce physics results. We consider seven sources of backgrounds, and for each source, the purity that will provide a non-dominant background subtraction error after six months of data taking. In practice, we quote the purity levels that will produce 150 electron tracks per day, with energy greater than 100 keV, but before any directional analysis. Subtraction errors add quadratically, so if any four sources considered are at the value quoted, the

background subtraction error would become non-dominant after one year. We make extensive use of the reduction factors calculated by R. Kessler elsewhere[8].

3.1 Cosmogenic backgrounds.

Regardless of depth, the dominating cosmogenic background for this TPC is the generation of ^{11}C(a positron emitter) in the inner plastic shield and methane. The only radioactive daughter from cosmogenesis in helium is tritium, which has an end-point of 17.6 keV, well below our 100 keV threshold. Cosmogenesis in the iron shell is also quite small, with no photons produced when a proton, neutron or α is extracted from ^{56}Fe.

In practice, the limiting depth factor is not so much the irreducible Compton backgrounds but rather the advantage of keeping the cosmic rate at or below 0.1 Hz (this corresponds to a depth of 2500 mwe), to minimize unnecessary vetos.

This class of backgrounds, at a depth of 2500 mwe, contributes less than ten events per day mostly due to the generation of ^{11}C in the inner plastic shield, and less in the methane. It is considered negligible and subsequently ignored.

3.2 Backgrounds from Surrounding Rock.

Simulations indicate that γ radiation from surrounding rock can be attenuated to negligible levels (ten events per day or less) with reasonable shielding[11]. For a rock purity of 5X10^{-8}g/g (WIPP site[12]), 3 mwe is sufficient. The Homestake site (rock purity 3X10^{-6}g/g [13]), will require an additional 1 mwe (4 mwe total) shielding. In our case most of the shielding is provided by the iron shell, which is required to be 30cm thick at Homestake and 20cm at WIPP.

Iron does not appreciably attenuate low energy neutrons[11], which have a flux about 1000 times lower than the γ. This source can be eliminated (less than one event per day) if a 5 cm plastic liner is inserted between the iron and the surrounding rock cavern (or, following the MUNU example[1], with 1 cm of boron-doped polyethylene). The plastic effectively stops the neutrons via the reaction $^1H(n,\gamma)d$ (if it is boron-doped, no photons will be emitted). The produced 2.2 MeV γ, if directed toward the active TPC region, is mostly absorbed by the iron shell and inner plastic shielding.

3.3 Backgrounds(γ's) Generated from within the Iron Shell.

If the overall steel purity is 10^{-11}g/g the amount of ^{238}U uniformly distributed throughout the iron shell volume is 0.04 grams. A 30 cm iron shell would effectly reduce this amount to 0.7 milligrams of ^{238}U placed uniformly at the surface of the iron/inner plastic interface. This amount is further attenuated by a factor of 10^3 by 100 cm of plastic before reaching the active TPC region. Therefore the effective contribution of this uranium impurity is equivalent to placing 0.7μgrams uniformly distributed on the inside surface of the TPC cage which generates $\sim$ 200 background events/day before directional analysis. In practice the photons which reach the TPC have a severely degraded

spectrum which further reduce the probability of generating 100 keV electrons by about a factor of three, or 0.23μgrams total.

3.4 Backgrounds Generated by the TPC Cage, Detector Planes and Inner Plastic Shielding.

A 10^{-12}g/g contamination of ^{238}U in the plastic (a purity similar to the limit obtained by SNO[14]) corresponds to 1.3 milligrams of ^{238}U uniformly distributed throughout the inner plastic shielding and TPC cage. The plastic self-shielding is equivalent to placing 50μgrams uniformly on the inside surface of the TPC cage. With some reduction factor due to energy degradation, there will be $\sim$ 15000 background events/day before directional analysis.

Clearly there is a need to go beyond the limits set by SNO[14], by two orders of magnitude, if this source is to be brought down to the level of the other sources. One possibility, of course, is that the true value is not just below the SNO limit. Another possibility is to have the last part of the plastic shield in the form of a deionized water vessel. Deionized water is known to have a radioactive contamination not exceeding 10^{-14}g/g. Clearly a major effort of the RD program is to find a viable solution to this problem.

Because of the much larger mass of the plastics compared to the active elements of the TPC (wires, strips, and grid, which are assumed to have a total weight of 30 kg) a purity of 3X10^{-11} g/g is needed for these elements, which is above the currently measured purity limits for OFHC and some steels (10^{-11}g/g).

3.5 ^{85}Kr Contamination.

^{85}Kr, which is a $\beta-$emitter, is only a background in our detector if it is introduced into our helium/methane gas mixture. ^{85}Kr was found to be a significant source of background by the Borexino Collaboration[15], is produced via nuclear fission of Uranium and Thorium, and has a half-life of 10.8 years. In an underground tunnel the air contains some ^{85}Kr and, in the case of Borexino, enough to contaminate their open air water shield.

It is unlikely that ^{85}Kr will be a problem for our TPC. Exposure to the underground air will be much less than that at the Borexino Counting Testing Facility, and at startup the TPC gas will be changed and vented several times before recirculation is started. This process should reduce the concentration of ^{85}Kr to negligible levels. We can also expect reductions from our cold trap as Krypton is liquid at 112K (see Table 1). The level of ^{85}Kr activity in our gas mixture must be kept below 0.7μBq/m^3($\sim$150 events/day).

3.6 Radon Contamination.

The effect of radon contamination in our gas mixture is largely reducible but must be kept at or below 0.7μBq/m^3($\sim$ 150 events/day before directional cuts). The Radon decay chain reads as

follows (half lives are in parentheses):

$$^{222}Rn(3.8d) \rightarrow^{218} Po(3.1m)+\alpha \rightarrow^{214} Pb(27m)+\alpha \rightarrow^{214} Bi(20m)+\beta+\gamma \rightarrow^{214} Po(160\mu sec)+\beta+\gamma$$

$$^{214}Po \rightarrow^{210} Pb(22y) + \alpha.$$

There are no appreciable backgrounds beyond ^{210}Pb for a chamber service period of order one year. The ^{214}Bi leg of the decay chain is reduced using the signature of a single electron followed by an α from the ^{214}Po decay within a 1/2 millisecond window. The predominant irreducible background comes from the ^{214}Pb beta decay.

The effect of the radon decay chain can be significantly reduced. In the presence of an electric field, the ion ^{218}Po, with a lifetime of a few minutes, drifts to the HV grid where it can bond chemically with the metal. In case of large radon contamination, the grid will itself become contaminated, however, it will also act as a radioactive trap, effectively segregating most of the ^{210}Pb and localizing the background level in z. Our TPC will be designed with a removable HV grid for easy service.

Radon was the dominant background for the MUNU[1] collaboration. Initially it was an unacceptably large source of background, until it was traced to an Oxysorb cartridge. These are chemically active filters which remove many compounds from a gas mixture. The cartridges are commercially made with little possibility of controlling their radiopurity. One of the goals of the R&D program is to explore all avenues that could lead to an Oxysorb-free gas circulation system.

After the MUNU collaboration changed its Oxysorb, the radon level stabilized to 10^{-3}Bq/m^3, see figure 14 in reference[1]. This value however is still three orders of magnitude above what we require.

There are three facts that point to a much smaller radon concentration in our TPC compared to MUNU. They are, in increasing order of importance:

1. A much larger volume to surface ratio, not only in the TPC but also between the TPC and the gas system, which should produce significant radon dilution (at least a factor of ten). The dilution factor should hold also when comparing this device to the GNO experiment discussed below.

2. With a slight overpressure inside the TPC cage, outgassing from the cage should be eliminated. This would greatly reduce radon levels, if the radon source is in the TPC cage. It will almost certainly suppress oxygen levels in the TPC gas and in turn possibly eliminate the need for an Oxysorb in the gas circuit.

3. A cold trap with a charcoal filter, similar to what has been implemented in the GNO experiment will be used. GNO achieved concentrations of 0.2μBq/m^3[10]. However our cold trap will operate at 112K, as opposed to the 77K used in GNO. The loss in radon capturing efficiency, due to the higher temperature, should be of order two or three[10].

3.7 Dust Contamination.

Dust entering the TPC active region will be of radiopurity similar to that of the surrounding rock and deposit itself on the inside wall of the TPC cage. However many low-background experiments have proven that dust contamination of surfaces can be greatly reduced by thorough cleaning with deionized water or distilled alcohol. The dust budget of our TPC, is ten grams at WIPP and 100 milligrams at Homestake($\sim$ 150 decays/day). Dust usually has a fairly invariant size distribution, peaking at or around 1 micron diameter. While larger dust will settle over days, sub-micron dust particles can remain airborne for weeks or months. A 0.05 micron dust filter should be able to remove more than 99% of all airborne dust. We have no data about the radiopurity of a dust filter, however such a filter has been used by the Borexino collaboration without any negative effects. We plan to insert a dust filter in the gas system only after each TPC access and then remove it when the TPC is in operation.

3.8 ^{14}C Contamination in the TPC Active Region

A substantial ^{14}C contamination does not eliminate a measurement of the all-important (*pp*) neutrino flux. The electron produced in the ^{14}C decay has an end-point energy of 156 keV. For (*pp*) neutrinos the maximum electron recoil energy is 217 keV. However observables sensitive to neutrino mixing, such as the electron recoil spectrum, and a distortion of the (*pp*) energy spectrum, would suffer since we would be sensitive to a smaller fraction of the total (*pp*) flux. There is no doubt that a high ^{14}C content would significantly affect the physics reach of the detector and therefore must be reduced to an acceptable level.

Our accompanying paper[9] describes a simulation where a ^{14}C/^{12}C ratio of $\sim$5X10^{-20} was assumed which generates $\sim$20 background events/day before directional cuts. We scale that result to find that the limit here (for 150 events/day) is $\sim$3X10^{-19}. A similar carbon purity requirement was found, for the case of CF_4 as a TPC gas, by Arpesella and Broggini[16].

3.8.1 ^{14}C Contamination in Methane Gas(CH_4).

The need for quenching requires the use of some fraction of methane in our Helium gas. Deep-well hydrocarbons are supposed to have maximal purity, with an estimated ^{14}C/^{12}C ratio of 5X10^{-21}[17]. Sources of ^{14}C consist mostly of nuclear interactions in the rock, such as the reaction ^{17}O(n,α)^{14}C[17]. The created ^{14}C is then assumed to form (or attach itself to) an hydrocarbon. Creation of ^{14}C in the petroleum or gas directly is due to neutron capture by ^{13}C, however it is considered only the third most important creation process[17]. The source of α's and neutrons for such reactions to take place are generated from the fission of uranium and thorium in the surrounding rock. Consequently the abundance of these elements in the adjacent rock should determine the level of ^{14}C. It is therefore natural to assume that the ^{14}C/^{12}C ratio in deep-well methane should vary from site to site.

In addition the ^{14}C content of methane should be significantly lower than that of petroleum or more complex hydrocarbon gases. The created ^{14}C will most likely react chemically with an existing

hydrocarbon and not with hydrogen molecules which are very scarce. This chemical process will create molecules with at least two carbon atoms which can be separated from methane via boil-off. We are currently trying to establish the chemical history of single carbon atoms in a deep-well environment to validate this hypothesis and discussions with geochemists have been started.

If our hypothesis is correct, then the dominant source of ^{14}C in methane is from neutron capture by ^{13}C. This implies that the ^{14}C content of methane could be highly variable. The level would depend not only on uranium concentration, but also on boron concentration. Further, the chemical history of the created ^{14}C is controlled via the chemical potentials by the local temperature and pressure.

The direct Borexino measurement of the ^{14}C content in their liquid scintillator[17] was found to be a factor of 190 higher than our requirement, or $1.9\text{X}10^{-18}$g/g. Originally explained as contamination by atmospheric carbon in the petrochemical plant, the problem has been reanalyzed by Schoenert [18]. According to Schoenert, there exists the possibility that the Borexino measurement does reflect the true content of ^{14}C in petroleum.

Even if the Borexino experiment measured the true content of ^{14}C, it did so only for the complex hydrocarbons(molecules with more that one carbon atom) that exist in their liquid scintillator. In fact a measurement of the ^{14}C content in deep-well methane was performed[19] and an upper limit of 1.6×10^{-18} was obtained. Even though we require a limit of one order of magnitude better, this result along with the Borexino measurement is consistent with our hypothesis.

If our hypothesis about the chemical history of single carbon is valid, it is possible that only methane or compounds synthesized from methane should be used. A goal of the R&D program is to determine adequate sources of methane that meet these requirements.

3.8.2 ^{14}C in the barrel.

Although it does not present a significant source of background, there will be ^{14}C in the TPC cage. The cage is separated into a barrel and two endcaps and will be discussed separately. ^{14}C decays in the barrel will result in tracks entering the active volume. While they will be easily eliminated by the selection cuts, it is important that the rate be low enough that such events do not generate unnecessary vetoes. In fact, if the results from Borexino are used, less than one hundred trackable electrons per day will enter the TPC, generating a negligible vetoing rate. ^{14}C decays will also generate γ rays via internal or external bremmstrahlung (this is true both for the barrel or the endcaps). In either case, the maximum energy of the γ is 156 keV, which can generate a maximum electron recoil energy of 58 keV, well below our threshold. In addition both bremmstrahlungs are suppressed, compared to the rate of electrons entering the TPC, by at least one order of magnitude.

3.8.3 ^{14}C in the endcaps.

The fundamental difference between ^{14}C in the endcaps and the barrel is that, if an electron track emanates from the endcap, it will be considered a candidate. These electrons have no clearly

reconstructed entry point in any material. If the Borexino measured ^{14}C content applies to all petroleum derivatives this background is not a problem. In such a case, there will be few tens of background events per day of this type.

Further cuts can only strongly suppress this background. The diffusion perpendicular to the track direction will be well measured, and that in turn measures the $z-$coordinate along the drift direction. The $z-$resolution is of order one meter for ten meters drift, but is of order a few centimeters near the detector plane. Such cuts would eliminate negligible amounts of signal events (by effectively shortening the active volume by a few centimeters).

3.9 Background Summary

A summary of estimated background rates, before signal cuts, from the the different sources is presented in Table 2. It's obvious from the the above discussions that the R&D program involving background reductions will involve determining adequate sources of methane, the design of a gas circulation system that reduces radioactive contaminations while not introducing new ones and an effective plastic/water inner shield.

Source	Requirements
Cosmogenesis	>1800 mwe overburden
Rock γ	3-4 mwe total shielding
Rock neutron	plastic liner
Iron Shell	1.5 mwe inner shielding (with $\sim 10^{-11}$g/g)
Inner Plastic Shielding and TPC Cage	3X10^{-13}g/g
Detector Planes	3X10^{-11}g/g
^{85}Kr in TPC Gas	0.7μBq/m^3
Radon in TPC Gas	0.7μBq/m^3
Dust on TPC Cage	100 mg - 10g
^{14}C in TPC Gas	$3X10^{-19}$ $^{14}C/^{12}C$
^{14}C in TPC Cage	10^{-17} $^{14}C/^{12}C$

Table 2: Summary of purity/shielding requirements. Each number refers to the level at which the background subtraction error becomes non-dominant after six months of data taking. If two numbers are quoted, the first refers to Homestake, and the second to WIPP.

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